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Table of Contents

I. Introduction

The purpose of this document is to define the radiation environment for the evaluation of degradation due to total ionizing and non-ionizing dose and of single event effects (SEEs) for the Laser Interferometry Space Antenna (LISA) instruments and spacecraft. The analysis took into account the radiation exposure for the nominal five-year mission at 20 degrees behind Earth's orbit of the sun, at 1 AU (astronomical unit) and assumes a launch date in 2014. The transfer trajectory out to final orbit has not yet been defined, therefore, this evaluation does not include the impact of passing through the Van Allen belts. Generally, transfer trajectories do not contribute significantly to degradation effects; however, single event effects and deep dielectric charging effects must be taken into consideration especially if critical maneuvers are planned during the Van Allen belt passes.

II. Radiation Environment

The natural space radiation environment of concern for damage to spacecraft electronics is classified into two populations, 1) the transient particles which include protons and heavier ions of all of the elements of the periodic table, and 2) the trapped particles which include protons, electrons and heavier ions. The trapped electrons have energies up to 10 MeV and the trapped protons and heavier ions have energies up to 100s of MeV. The transient radiation consists of galactic cosmic ray particles and particles from solar events (coronal mass ejections and flares). The cosmic rays have low-level fluxes with energies up to TeV. The solar eruptions periodically produce energetic protons, alpha particles, heavy ions, and electrons. The solar protons have energies up to 100's MeV and the heavier ions reach the GeV range. All particle fluxes are isotropic and omnidirectional to the first order.

Space also contains low energy plasma of electrons and protons with fluxes up to 10^{12} cm^2/sec. The plasmasphere environment and the low energy (< 0.1 MeV) component of the charged particles are a concern in the near-earth environment. In the outer regions of the magnetosphere and in interplanetary space, the plasma is associated with the solar wind. Because of its low energy, thin layers of material easily stop the plasma so it is not a hazard to most spacecraft electronics. However, it is damaging to surface materials and differentials in the plasma environment can contribute to spacecraft surface charging and discharging problems [1,2].

III. Description of Radiation Effects

Radiation effects that are important to consider for instrument and spacecraft design fall roughly into three categories: degradation from total ionizing dose (TID), degradation from non-ionizing energy loss (NIEL), and single event effects (SEE). Total ionizing dose in electronics is a cumulative, long-term degradation mechanism due to ionizing radiation—mainly primary protons and electrons and secondary particles arising from interactions between these primary particles and spacecraft materials. It causes threshold shifts, leakage current and timing skews. The effect first appears as parametric degradation of the device and ultimately results in functional failure. It is possible to reduce TID with shielding material that absorbs most electrons and lower energy protons. As shielding is increased, shielding effectiveness decreases because of the difficulty in slowing down the higher energy protons. When a manufacturer advertises a part as "rad-hard", he is almost always referring to its total ionizing dose characteristics. Rad-hard does not

usually imply that the part is hard to non-ionizing dose or single event effects. In some cases, a “rad-hard” part may perform significantly worse in the space radiation environment than in the test environment (e.g. Enhanced Low Dose Rate Sensitivity in linear bipolar devices.)

Displacement damage is cumulative, long-term non-ionizing damage due to protons, electrons, and neutrons. These particles produce defects in optical materials that result in charge transfer degradation. Displacement damage affects the performance of optocouplers (often a component in power devices), solar cells, CCDs, and linear bipolar devices. The effectiveness of shielding depends on the location of the device. For example, coverglasses over solar cells reduce electron damage and proton damage by absorbing the low energy particles. Increasing shielding beyond a critical threshold, however, is not usually effective for optoelectronic components because the high-energy protons penetrate the most feasible spacecraft electronic enclosures. For detectors in instruments it is necessary to understand the instrument technology and geometry to determine the vulnerability to the environment.

Single event effects (SEE) result from ionization by a single charged particle as it passes through a sensitive junction of an electronic device. SEE are caused by heavier ions, but for some devices, protons can also contribute. In some cases SEEs are induced through direct ionization by the proton, but in most instances, proton induced effects result from secondary particles produced when the proton scatters off of a nucleus in the device material. Some single event effects are non-destructive, as in the case of single event upsets (SEUs), single event transients (SETs), multiple bit errors (MBEs), single event hard errors (SHEs), etc. Single event effects can also be destructive as in the case of single event latchups (SELs), single event gate ruptures (SEGRs), and single event burnouts (SEBs). The severity of the effect can range from noisy data to loss of the mission, depending on the type of effect and the criticality of the system in which it occurs. Shielding is not an effective mitigator for single event effects because they are induced by very penetrating high-energy particles. The preferred method for dealing with destructive failures is to use SEE-hard parts. When SEE-hard parts are not available, latchup protection circuitry is sometimes used in conjunction with failure mode analysis. (Note: Care is necessary when using SEL protection circuitry, because SEL may damage a microcircuit and reduce its reliability even when it does not cause outright failure.) For non-destructive effects, mitigation takes the form of error-detection and correction codes (EDACs), filtering circuitry, etc.

Total ionizing dose is primarily caused by protons and electrons trapped in the Van Allen belts and solar event protons. As electrons are slowed down, their interactions with orbital electrons of the shielding material produce a secondary photon radiation known as bremsstrahlung. Generally, the dose due to galactic cosmic ray ions and proton secondaries is negligible compared to other sources. For surface degradation, it is also important to include the effects of very low energy particles.

Single event effects can be induced by heavy ions (solar events and galactic cosmic rays) and, in some devices, protons (trapped and solar events) and neutrons. Displacement damage is primarily due to trapped and solar protons and also neutrons that are produced by interactions of primary particles with the atmosphere and spacecraft materials.[*] High-energy electrons can also contribute to displacement damage, especially for lightly shielded applications. Spacecraft charging can occur on the surface of the spacecraft due to low energy electrons. Deep dielectric charging occurs when high-energy electrons penetrate the spacecraft and collect in dielectric materials.

[*] In avionics applications it is necessary to consider neutrons that are produced by interactions of primary particles with the atmosphere.

IV. The LISA Mission

The LISA spacecraft will be transferred out to their final orbit via a trajectory that has not yet been defined. While in the transfer, LISA will pass through the trapped proton and electron belts. These exposures could constitute a single event effect risk during some maneuvers but will not contribute to significant degradation effects. During the transfer trajectory, LISA spacecraft will also encounter varying levels of galactic cosmic ray heavy ions and possibly protons and heavier ions from solar events. It will also be necessary to take the charging effects of the trapped electrons into account.

Once LISA spacecraft reach their final orbit, their mission requirement is 5 years, and their mission goal is 10 years. With an expected 2014 launch year, the LISA mission will occur during the decreasing phase of the active phase of the solar cycle 24 (the peak of the active phase of solar cycle 24 is expected to occur some time between 2012 and 2014) and at the transition to solar cycle 25. During the active phase of the sun, the likelihood that the spacecraft will be exposed to particles from solar events (either solar flare or coronal mass ejections) increases significantly. Based on an average 11-year solar cycle, the LISA mission will encounter 3 years of solar active conditions. The 10 years extended mission will encounter 7 years of solar active conditions. The radiation environment encountered by the LISA spacecraft will consist of protons and heavier ions from solar events, galactic cosmic ray heavy ions, and solar wind plasma consisting of low energy protons, electrons, and heavier ions.

V. Total Dose and Degradation

The total ionizing dose accumulation causes performance degradation and failure on memories, power converters, etc. Non-ionizing energy loss in materials (atomic displacement damage) causes degradation of solar cells, optoelectronics, and detectors. The low energy particles also contribute to the erosion of surfaces.

A. Degradation Environment

1. The Plasma Environment

At LISA orbit, low energy particles from the solar wind plasma contribute to the degradation of surface materials and also cause charging effects. These charging effects should be considered in the spacecraft design. However, the plasma environment does not contribute to significant degradation effects.

2. High Energy Particles – Spacecraft Incident Fluences

The spacecraft incident proton fluence levels given in this document are most often used for standard solar cell analyses that take into account the coverglass thickness of the cell. There are three possible sources of high energy particles: trapped protons and trapped electrons encountered in the transfer trajectory and protons from solar events that can occur anytime during the three to seven solar active years of the mission. The trapped particles encountered in the transfer trajectory cannot be evaluated at this time but are usually not a factor in degradation analyses. The proton fluence levels are also used to determine displacement damage effects, however, most analysis methods require that the surface incident particles be transported through the materials surrounding the sensitive components. The proton fluences behind nominal aluminum shield thicknesses are given in Section V.A.3.

When the transfer trajectory is known, the trapped particle fluxes will be estimated with NASA's AP-8 [3] model for protons and AE-8 [4] model for electrons. The models come in solar minimum and maximum versions. The uncertainty factors defined for the models are a factor of 2 for the AP-8 and 2 to 5 for the AE-8. These uncertainty factors apply to long term averages expected over a 6-month mission duration. Daily values can fluctuate by two to three orders of magnitude depending on the level of activity on the sun and within the magnetosphere.

The solar proton levels can now be estimated from the Emission of Solar Proton (ESP) model [5]. The ESP model is based on satellite data from solar cycles 20, 21, and 22. The distribution of the fluences for the events is obtained from maximum entropy theory, and design limits in the worst case models are obtained from extreme value theory.

Total integral solar proton fluences were estimated for 3 to 7 solar active years with 3 years being the number of years to consider for the nominal mission and 7 years the number of years to consider for the 10 years extended mission. **Table A1** gives the fluence levels as a function of particle energy for 95%

confidence levels. **Figure** 1 is a plot of the energy-fluence spectra for 3 and 7 solar active years for a 95% confidence level. The energies are in units of >MeV and the fluences are in units of particles/cm^2. These values do not include a design margin. The solar proton predictions are not linear over time; therefore, these estimates may be invalid if extrapolated for longer or shorter mission durations.

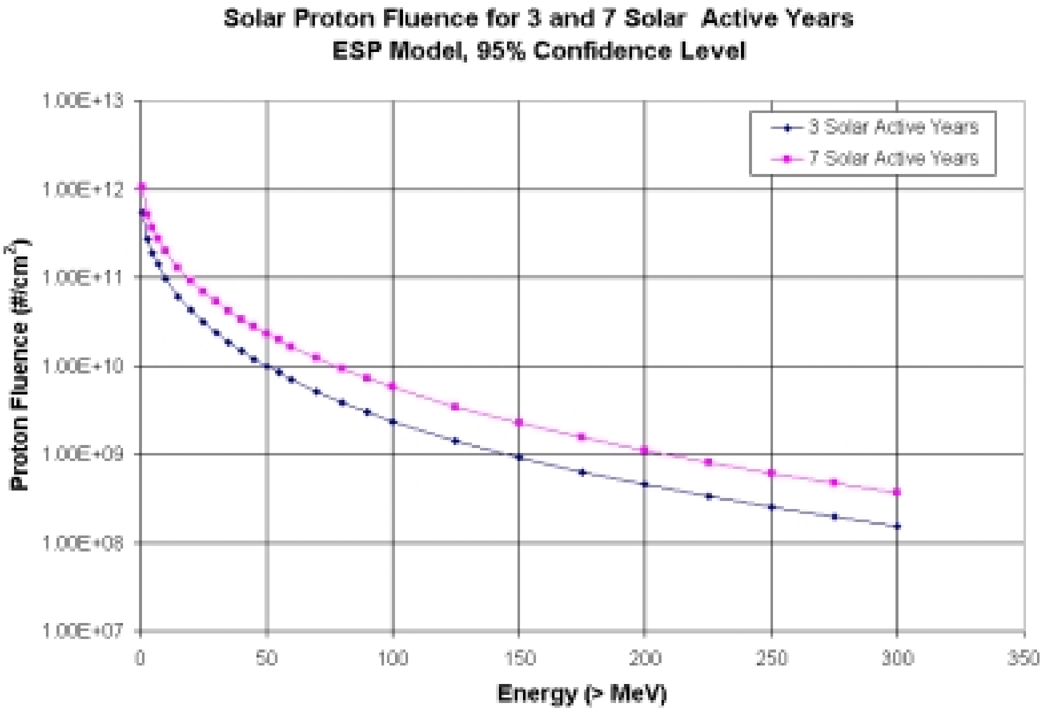

Figure 1: Solar proton fluences for a 95% confidence level are presented for 3 and 7 solar active years.

3. High Energy Particles – Shielded Fluences

Evaluation of non-ionizing energy loss damage requires the use of shielded fluence levels. For this analysis, nominal shielding thicknesses of 100 mils of aluminum were used for a generic solid sphere geometry. The spacecraft incident, solar proton estimates for the 95% confidence level and for 3 and 7 solar active years were transported through the shield thickness to obtain fluence estimates behind the shielding. **Table A2** gives the degraded energy spectra. The spectra are plotted in **Figure 2**. It can be seen from the figures that even though low energy particles are absorbed by the shielding, the low energy range of the spectrum is filled in by the higher energy protons as they are degraded by passing through the material.

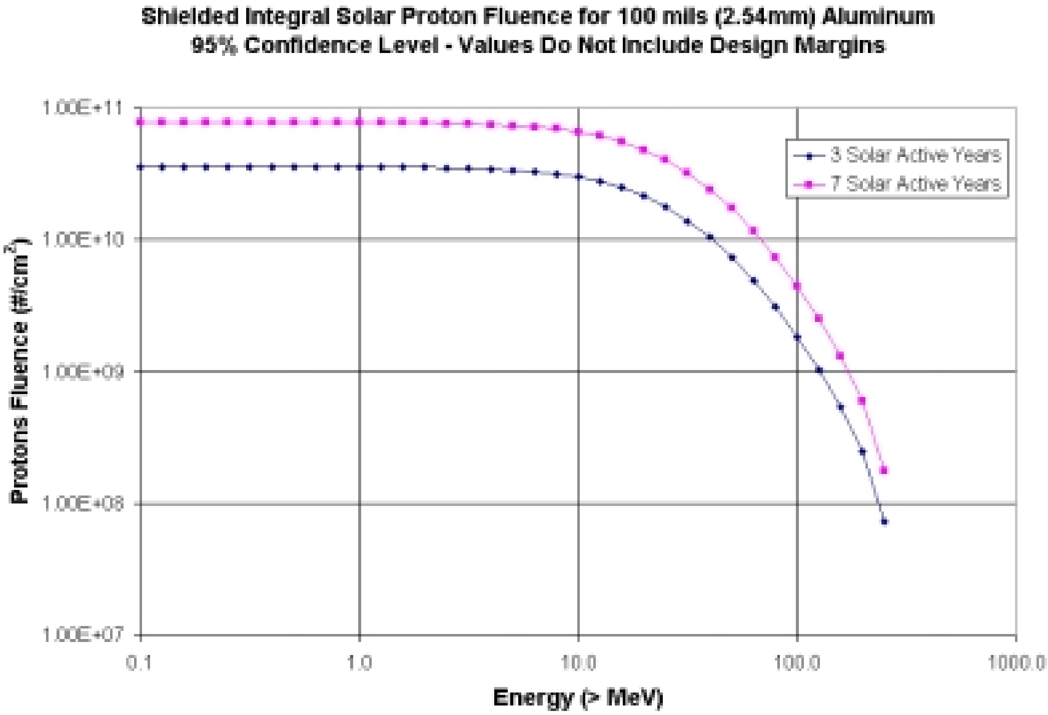

Figure 2: Shielded solar proton energy spectra for 100 mils aluminum, 95% confidence level

B. Total Dose Estimates

1. Top Level Ionizing Dose Requirement

Doses are calculated from the surface incident integral fluences as a function of aluminum shield thickness for a simple geometry. The geometry model used for spacecraft applications is the solid sphere. The solid sphere doses represent an upper boundary for the dose inside an actual spacecraft and are used as a top-level requirement. In cases where the amount of shielding surrounding a sensitive location is difficult to estimate, a more detailed analysis of the geometry of the spacecraft structure may be necessary to evaluate the expected dose levels. This is done by modeling the electronic boxes or instruments and the spacecraft structure. The amount of shielding surrounding selected sensitive locations is estimated using solid angle sectoring and 3-dimensional ray tracing. Doses obtained by sectoring methods must be verified for 5-10% of the sensitive locations with full Monte Carlo simulations of particle trajectories through the structure for many histories.

Table A3 and **Figures 3** give the top-level total ionizing dose requirement for the 5 year LISA mission and for the 10 year extended mission. The doses are given for 3 and 7 solar active years for a 95% confidence level. The best estimate at this time predicts 3 solar active years for the nominal mission and 7 solar active years for the extended mission given the 2012 LISA launch. The doses are calculated here as a function of aluminum shield thickness in units of krads in silicon. For the nominal 100 mils of equivalent aluminum shielding and the 5 years nominal mission, the dose requirement is 14 krad-Si with no design margin. For

the nominal 100 mils of equivalent aluminum shielding and the 10 years extended mission , the dose requirement is 29 krad-Si with no design margin A minimum design margin of x 2 is recommended.

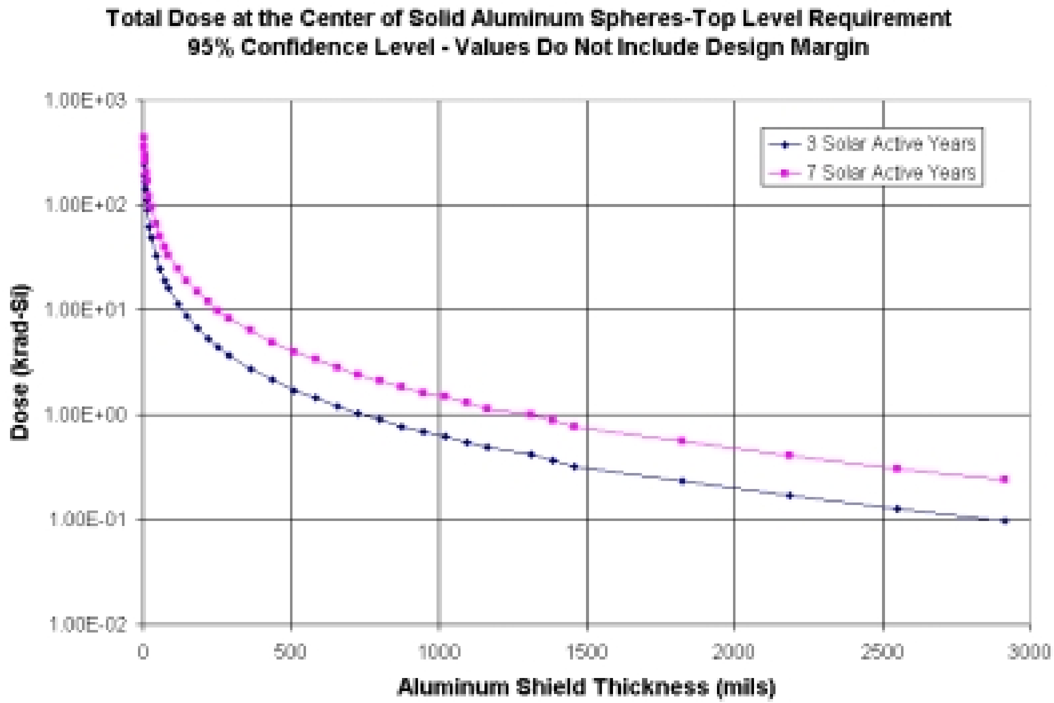

Figure 11: Total ionizing dose from solar proton events for 3 and 7 solar active years

2. Dose at Specific Spacecraft Locations

In cases where parts cannot meet the top level design requirement and a "harder" part cannot be substituted, it is often beneficial to employ more accurate methods of determining the dose exposure for some spacecraft components to qualify the parts. One such method for calculating total dose, solid angle sectoring/3-dimensional ray tracing, is accomplished in three steps:

1) Model the spacecraft structure:
   - develop a 3-D model of the spacecraft structures and components
   - develop a material library
   - define sensitive locations
2) Model the radiation environment:
   - define the spacecraft incident radiation environment
   - develop a particle attenuation model using theoretical shielding configurations (similar to dose-depth curves).
3) Obtain results for each sensitive location:
   - divide the structural model into solid angle sectors
   - ray trace through the sectors to calculate the material mass distribution
   - use the ray trace results to calculate total doses from the particle attenuation model.

Once the basic structural model has been defined, total doses can be obtained for any location in the spacecraft in a short time (in comparison to Monte Carlo methods). The value of dose mitigation measures can be accurately evaluated be adding the changes to the model and recalculating the total dose. For spacecraft with strict weight budgets, the 3-D ray trace method, the total dose design requirement can be defined at a box or instrument level avoiding unnecessary use of expensive or increasingly unavailable radiation hardened parts.

As the design of the LISA evolves, it may become necessary to estimate the doses at specific locations in the spacecraft or instruments. Often the dose requirement can be met by modeling the surrounding electronic box only or by modeling only the instrument.

C. Displacement Damage Estimates

Total non-ionizing energy loss damage is evaluated by combining the shielded proton energy spectra given Section V.A.3 with the NIEL Non Ionizing Energy Loss (NIEL) response curves for the material and the results of laboratory radiation of the devices sensitive to atomic displacement damage. The level of the hazard is highly dependent on the device type and can be process specific. For the LISA mission, it is important to keep in mind that some optoelectronic devices experience enough damage during one large solar proton event to cause the device to fail. It is necessary that the parts list screening for radiation also include a check for devices that are susceptible to displacement damage.

VI. Single Event Effects Analysis

A. *Heavy Ion Induced Single Event Effects*

Some electronic devices are susceptible to single event effects (SEEs), e.g., single event upsets, single event latch-up, single event burn-out. Because, they are highly ionizing and penetrating, energetic GCR and solar heavy ions cause SEEs by the direct deposit of charge. The quantity most frequently used to measure an ion's ability to deposit charge in devices is linear energy transfer (LET). Heavy ion abundances and energy distributions are converted to total LET spectra. Once specific parts are selected for the mission and, if necessary, characterized by laboratory testing, the LET spectra for the heavy ions in the space radiation environment are integrated with the device characterization to calculate SEE rates. Heavy ion populations that have sufficient numbers to be a SEE hazard are the galactic cosmic rays and those from solar events.

1. Galactic Cosmic Rays

The cosmic ray fluxes for elements hydrogen through uranium were used to calculate daily LET spectra for 100 mils nominal aluminum shielding as given in **Table A4** and **Figure 4**. The range of the cosmic ray abundances is bounded by the extremes of the solar active and inactive phases of the solar cycle with the highest values occurring during the solar inactive phase and the lowest during the solar active phase. With the extended mission goal of 10 years, the highest values should be used for single event effects analyses. The LET fluence values are given for the highest and lowest point of the solar cycle. The CREME96 [6] model was used to obtain the cosmic ray heavy ion abundances. This model has an accuracy of 25-40%.

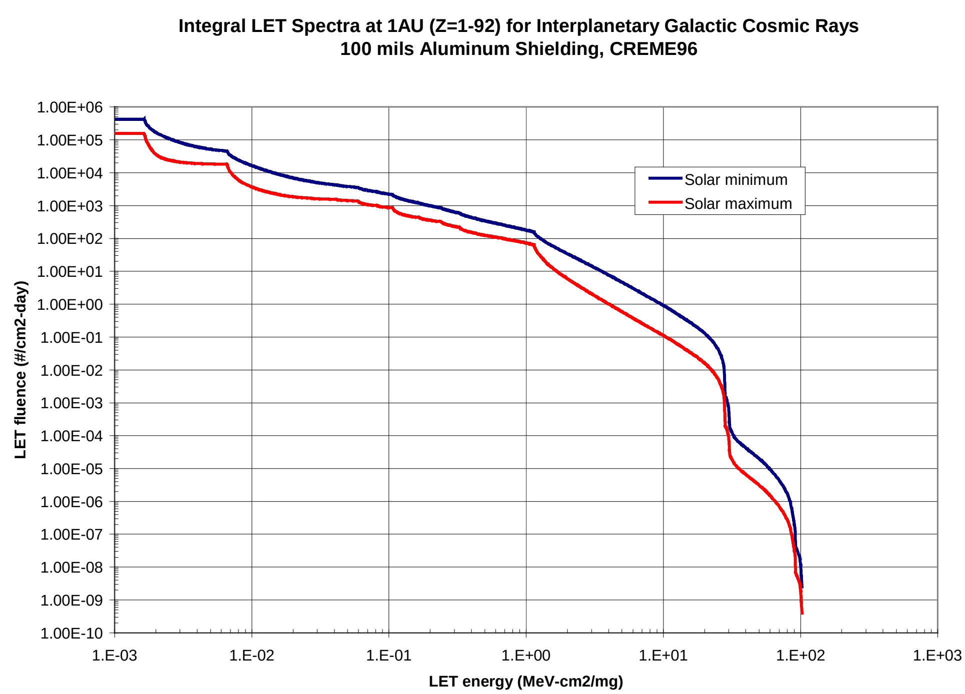

Figure 4: Integral LET spectra are shown for galactic cosmic ray ions hydrogen through uranium.

2. Solar Heavy Ions

The heavy ions from solar flares and coronal mass ejections can also produce single event effects. The solar event fluxes for the elements hydrogen through uranium were used to calculate daily LET spectra for 100 mils nominal aluminum shielding in units of average LET flux per second. The intensity of the fluxes varies over the duration of an event; therefore, values are averaged over the worst week of the solar cycle, the worst day of the solar cycle, and the peak of the October 1989 solar event. **Table A5** and **Figure 5** give the solar heavy ion LET predictions for the LISA mission. The new CREME96 model was also used to calculate the solar heavy ion levels. An uncertainty factor for the solar heavy ion model has not been released.

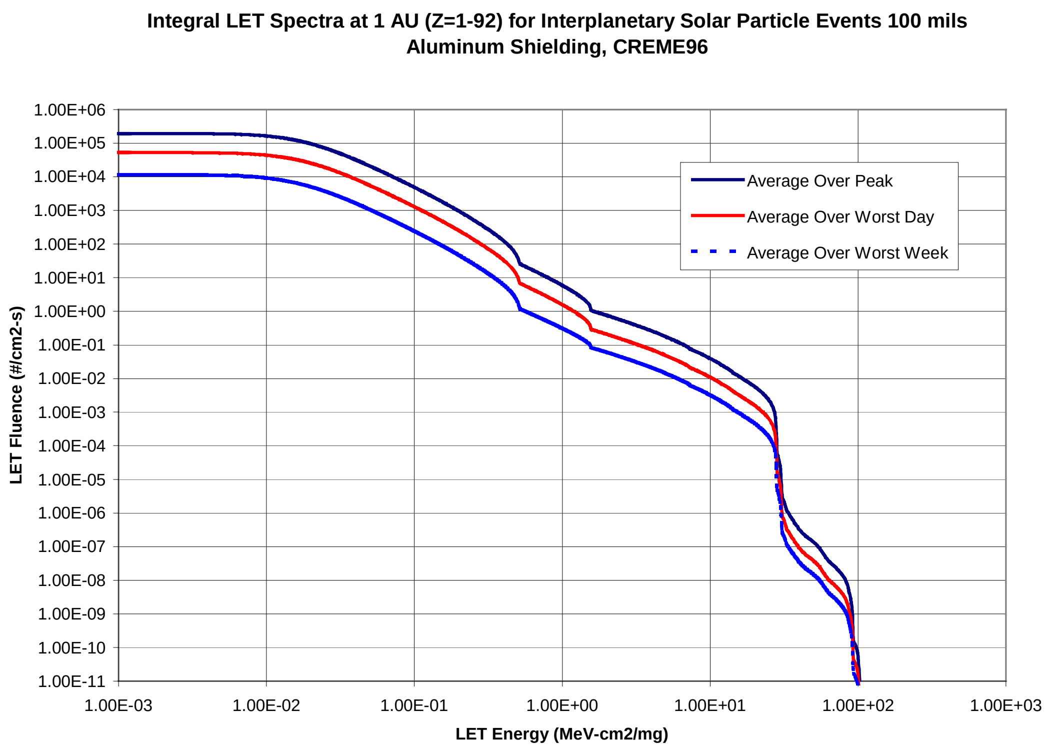

Figure 5: Integral LET spectra are shown for hydrogen through uranium for the October 1989 solar particle event.

B. Proton Induced Single Event Effects

In some devices, single event effects are also induced by protons. Protons from the trapped radiation belts and from solar events do not generate sufficient ionization (LET < 1 MeV-cm^2/mg) to produce the critical charge necessary for SEEs to occur in most electronics. More typically, protons cause Single Event Effects through secondary particles via nuclear interactions, that is, spallation and fractionation products. Because the proton energy is important in the production (and not the LET) of the secondary particles that cause the SEEs, device sensitivity to these particles is typically expressed as a function of proton energy rather than LET.

1. Trapped Protons

Trapped protons can be a concern for single event effects during the transfer trajectory passes through the trapped particle radiation belts. The proton fluxes in the intense regions of the belts reach levels that are high enough to pose a significant risk for upsets or latchups. The timing of critical operations during the transfer trajectory should be analyzed to determine the trapped proton environment at the time of the operation.

2. Solar Protons

Protons from solar events can also be a single event effects hazard for the LISA spacecraft. These enhanced levels of protons could occur anytime during the 5 to 10 year mission but are most likely during the portion of the mission that occurs during the active phase of the solar cycle. As with the solar heavy ion LET, solar proton fluxes are averaged over worst day, worst week, and the peak of the October 1989 solar event. The proton flux averages for a nominal 100 mils of shielding are given in **Table A6** and are shown in **Figure 6**.

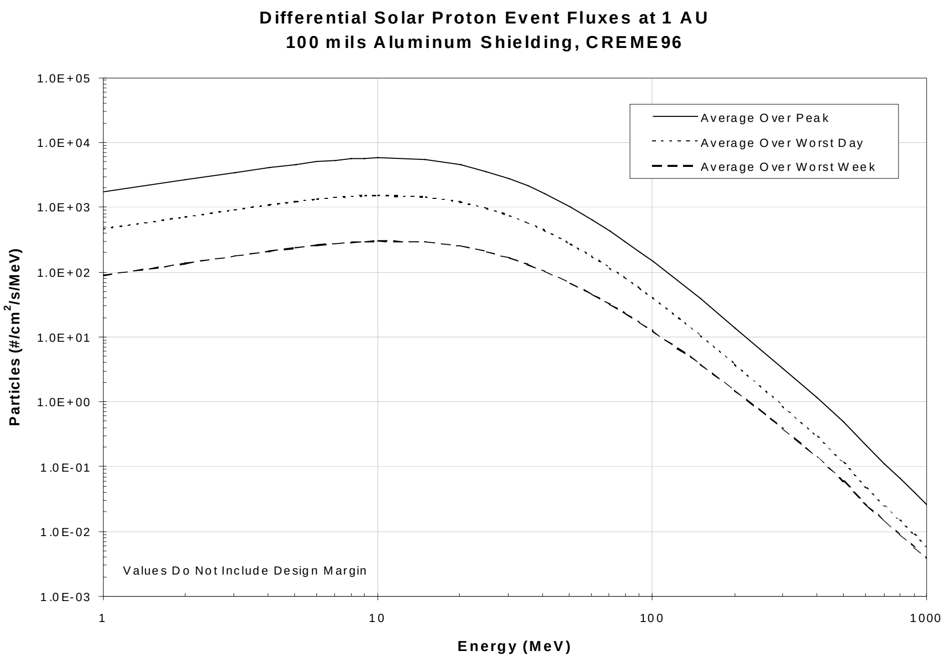

Figure 6: Solar proton fluxes for single event effects evaluation.

VII. Spacecraft Charging and Discharging

Surface charging and deep dielectric charging must also be evaluated for the LISA mission. Both are potential problems in transfer trajectories that take long loops through the Van Allen belts. During these loops, the spacecraft can accumulate high levels of electron build-up on spacecraft surfaces (low energy electrons) in the dielectrics (high energy electrons). Surface charging is also a concern during the entire mission when the spacecraft reaches its final orbit due to the plasma environment.

VIII. Summary

A top-level radiation environment specification was presented for the LISA mission. Although the environment is considered “moderate”, the environment poses challenges to mission designers because of its highly variable nature caused by activity on the sun.

Spacecraft and instrument designers must be made aware that some newer technologies and commercial-off-the-shelf (COTS) devices are very soft to radiation effects. COTS devices that lose functionality at 5 krads of dose are not uncommon. One extremely large solar proton event can cause enough displacement damage degradation in some optocoupler devices to cause failure. Increasingly, single event effects require careful part selection and mitigation schemes. With its full exposure to galactic cosmic heavy ions and particles from solar events, LISA must have a carefully planned radiation engineering program.

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Appendices

Table A1
Spacecraft Incident Solar Proton Fluences for 3 to 7 Solar Active Years
Values Do Not Include Design Margins

Energy	Number of Solar Active Years (95% confidence level)				
(> MeV)	3	4	5	6	7
1	5.48E+11	6.80E+11	8.06E+11	9.28E+11	1.05E+12
3	2.76E+11	3.42E+11	4.04E+11	4.62E+11	5.17E+11
5	1.87E+11	2.34E+11	2.78E+11	3.19E+11	3.57E+11
7	1.39E+11	1.76E+11	2.10E+11	2.42E+11	2.72E+11
10	9.75E+10	1.25E+11	1.50E+11	1.74E+11	1.97E+11
15	6.15E+10	7.98E+10	9.72E+10	1.14E+11	1.29E+11
20	4.25E+10	5.57E+10	6.82E+10	8.03E+10	9.19E+10
25	3.11E+10	4.10E+10	5.05E+10	5.97E+10	6.86E+10
30	2.36E+10	3.13E+10	3.87E+10	4.59E+10	5.29E+10
35	1.84E+10	2.45E+10	3.05E+10	3.63E+10	4.19E+10
40	1.47E+10	1.97E+10	2.45E+10	2.92E+10	3.39E+10
45	1.20E+10	1.61E+10	2.00E+10	2.39E+10	2.78E+10
50	9.92E+09	1.33E+10	1.66E+10	1.99E+10	2.31E+10
55	8.29E+09	1.11E+10	1.40E+10	1.67E+10	1.94E+10
60	7.01E+09	9.43E+09	1.18E+10	1.42E+10	1.65E+10
70	5.14E+09	6.94E+09	8.72E+09	1.05E+10	1.22E+10
80	3.88E+09	5.25E+09	6.61E+09	7.96E+09	9.29E+09
90	3.00E+09	4.06E+09	5.12E+09	6.17E+09	7.21E+09
100	2.36E+09	3.20E+09	4.04E+09	4.88E+09	5.71E+09
125	1.42E+09	1.93E+09	2.44E+09	2.94E+09	3.44E+09
150	9.22E+08	1.25E+09	1.58E+09	1.90E+09	2.23E+09
175	6.32E+08	8.56E+08	1.08E+09	1.30E+09	1.53E+09
200	4.52E+08	6.12E+08	7.73E+08	9.33E+08	1.09E+09
225	3.33E+08	4.52E+08	5.70E+08	6.88E+08	8.04E+08
250	2.52E+08	3.41E+08	4.31E+08	5.20E+08	6.08E+08
275	1.94E+08	2.64E+08	3.33E+08	4.01E+08	4.69E+08
300	1.53E+08	2.07E+08	2.62E+08	3.16E+08	3.69E+08

Table A2

Integral Solar Proton Fluence Levels Behind Solid Sphere Aluminum Shields

100 mils (2.54 mm) Aluminum Shielding – 95% Confidence Level

Values Do Not Include Design Margins

Degraded Energy	Shielded Solar Proton Fluence	
	3 Solar Active Years	7 Solar Active Years
(> MeV)	(#/cm^2)	(#/cm^2)
1.00E-01	3.57E+10	7.79E+10
1.26E-01	3.57E+10	7.79E+10
1.58E-01	3.57E+10	7.79E+10
2.00E-01	3.57E+10	7.79E+10
2.51E-01	3.57E+10	7.79E+10
3.16E-01	3.57E+10	7.79E+10
3.98E-01	3.57E+10	7.78E+10
5.01E-01	3.57E+10	7.78E+10
6.31E-01	3.57E+10	7.78E+10
7.94E-01	3.56E+10	7.77E+10
1.00E+00	3.56E+10	7.76E+10
1.26E+00	3.55E+10	7.75E+10
1.58E+00	3.54E+10	7.73E+10
2.00E+00	3.53E+10	7.70E+10
2.51E+00	3.51E+10	7.66E+10
3.16E+00	3.48E+10	7.59E+10
3.98E+00	3.43E+10	7.50E+10
5.01E+00	3.37E+10	7.36E+10
6.31E+00	3.27E+10	7.18E+10
7.94E+00	3.16E+10	6.94E+10
1.00E+01	2.99E+10	6.60E+10
1.26E+01	2.77E+10	6.14E+10
1.58E+01	2.48E+10	5.53E+10
2.00E+01	2.14E+10	4.81E+10
2.51E+01	1.77E+10	4.02E+10
3.16E+01	1.39E+10	3.20E+10
3.98E+01	1.04E+10	2.41E+10
5.01E+01	7.38E+09	1.73E+10
6.31E+01	4.88E+09	1.16E+10
7.94E+01	3.06E+09	7.35E+09
1.00E+02	1.82E+09	4.41E+09
1.26E+02	1.03E+09	2.51E+09
1.58E+02	5.37E+08	1.31E+09
2.00E+02	2.46E+08	5.94E+08
2.51E+02	7.24E+07	1.76E+08

Table A3
Total Ionizing Dose at the Center of Aluminum Spheres Due to Solar Proton Events
95% Confidence Level
Values Do Not Include Design Margins

Aluminum Shield Thickness			**3 Solar Active Years**	**7 Solar Active Years**
g/cm^2	**mm**	**mils**	**(krad-Si)**	**(krad-Si)**
0.03	0.11	4.37	2.44E+02	4.44E+02
0.04	0.15	5.83	1.93E+02	3.52E+02
0.05	0.19	7.29	1.64E+02	2.99E+02
0.06	0.22	8.75	1.40E+02	2.56E+02
0.08	0.30	11.67	1.11E+02	2.05E+02
0.10	0.37	14.58	9.10E+01	1.70E+02
0.15	0.56	21.87	6.29E+01	1.20E+02
0.20	0.74	29.16	4.87E+01	9.48E+01
0.30	1.11	43.74	3.26E+01	6.50E+01
0.40	1.48	58.31	2.46E+01	5.00E+01
0.50	1.85	72.91	1.90E+01	3.92E+01
0.60	2.22	87.48	1.59E+01	3.33E+01
0.80	2.96	116.65	1.15E+01	2.44E+01
1.00	3.70	145.83	8.81E+00	1.90E+01
1.25	4.63	182.28	6.79E+00	1.48E+01
1.50	5.56	218.74	5.36E+00	1.19E+01
1.75	6.48	255.16	4.35E+00	9.78E+00
2.00	7.41	291.61	3.64E+00	8.30E+00
2.50	9.26	364.53	2.77E+00	6.33E+00
3.00	11.11	437.40	2.15E+00	4.94E+00
3.50	12.96	510.24	1.72E+00	3.97E+00
4.00	14.81	583.07	1.44E+00	3.34E+00
4.50	16.67	656.30	1.21E+00	2.82E+00
5.00	18.52	729.13	1.03E+00	2.42E+00
5.50	20.37	801.97	9.00E-01	2.11E+00
6.00	22.22	874.80	7.77E-01	1.83E+00
6.50	24.07	947.64	6.90E-01	1.63E+00
7.00	25.93	1020.87	6.17E-01	1.47E+00
7.50	27.78	1093.70	5.48E-01	1.31E+00
8.00	29.63	1166.54	4.85E-01	1.15E+00
9.00	33.33	1312.20	4.16E-01	9.94E-01
9.50	35.19	1385.43	3.66E-01	8.81E-01
10.00	37.04	1458.27	3.18E-01	7.69E-01
12.50	46.30	1822.83	2.31E-01	5.60E-01
15.00	55.56	2187.40	1.68E-01	4.07E-01
17.50	64.81	2551.57	1.26E-01	3.05E-01
20.00	74.07	2916.14	9.84E-02	2.38E-01

Table A4
Integral LET for Interplanetary Galactic Cosmic Rays (Z=1-92)
100 mils Aluminum Shielding
Values Do Not Include Design Margins

Solar Minimum Activity		**Solar Maximum Activity**	
LET (MeV*cm^2/mg)	**LET Fluence (#/cm^2/day)**	**LET (MeV*cm^2/mg)**	**LET Fluence (#/cm^2/day)**
1.00E-03	4.25E+05	1.00E-03	1.54E+05
1.65E-03	4.24E+05	1.65E-03	1.54E+05
1.69E-03	3.29E+05	1.69E-03	1.07E+05
1.70E-03	3.04E+05	1.70E-03	9.42E+04
1.72E-03	2.84E+05	1.72E-03	8.46E+04
1.77E-03	2.54E+05	1.77E-03	7.02E+04
1.81E-03	2.30E+05	1.81E-03	5.98E+04
1.85E-03	2.12E+05	1.85E-03	5.20E+04
1.91E-03	1.90E+05	1.91E-03	4.34E+04
1.98E-03	1.72E+05	1.98E-03	3.75E+04
2.01E-03	1.67E+05	2.01E-03	3.59E+04
2.13E-03	1.46E+05	2.13E-03	3.05E+04
2.28E-03	1.27E+05	2.28E-03	2.69E+04
2.53E-03	1.07E+05	2.53E-03	2.39E+04
3.01E-03	8.29E+04	3.01E-03	2.11E+04
3.54E-03	6.87E+04	3.54E-03	1.98E+04
4.52E-03	5.55E+04	4.52E-03	1.88E+04
5.56E-03	4.90E+04	5.56E-03	1.83E+04
6.54E-03	4.58E+04	6.54E-03	1.82E+04
7.52E-03	2.76E+04	7.52E-03	7.46E+03
8.55E-03	2.13E+04	8.55E-03	5.04E+03
9.60E-03	1.75E+04	9.60E-03	3.97E+03
1.97E-02	7.02E+03	1.97E-02	1.88E+03
2.96E-02	5.07E+03	2.96E-02	1.63E+03
4.00E-02	4.33E+03	4.00E-02	1.55E+03
5.04E-02	3.81E+03	5.04E-02	1.43E+03
6.00E-02	3.50E+03	6.00E-02	1.36E+03
6.97E-02	2.91E+03	6.97E-02	1.08E+03
8.01E-02	2.66E+03	8.01E-02	1.01E+03
9.00E-02	2.40E+03	9.00E-02	9.12E+02
1.01E-01	2.23E+03	1.01E-01	8.74E+02
2.00E-01	9.84E+02	2.00E-01	3.59E+02
4.02E-01	4.33E+02	4.02E-01	1.52E+02

Table A4 (Continued)
Integral LET for Interplanetary Galactic Cosmic Rays (Z=1-92)
100 mils Aluminum Shielding
Values Do Not Include Design Margins

Solar Minimum Activity		**Solar Minimum Activity**	
LET (MeV*cm^2/mg)	**LET Fluence (#/cm^2/day)**	**LET (MeV*cm^2/mg)**	**LET Fluence (#/cm^2/day)**
6.03E-01	2.90E+02	6.03E-01	1.10E+02
7.96E-01	2.23E+02	7.96E-01	8.84E+01
1.00E+00	1.79E+02	1.00E+00	7.22E+01
2.01E+00	3.39E+01	2.01E+00	5.88E+00
3.02E+00	1.43E+01	3.02E+00	2.03E+00
3.99E+00	7.76E+00	3.99E+00	1.02E+00
5.03E+00	4.59E+00	5.03E+00	5.81E-01
5.99E+00	3.07E+00	5.99E+00	3.80E-01
8.00E+00	1.55E+00	8.00E+00	1.90E-01
1.01E+01	9.00E-01	1.01E+01	1.10E-01
1.11E+01	7.17E-01	1.11E+01	8.75E-02
1.20E+01	5.76E-01	1.20E+01	7.04E-02
1.30E+01	4.67E-01	1.30E+01	5.71E-02
1.40E+01	3.85E-01	1.40E+01	4.72E-02
1.50E+01	3.16E-01	1.50E+01	3.88E-02
1.60E+01	2.61E-01	1.60E+01	3.20E-02
1.70E+01	2.20E-01	1.70E+01	2.71E-02
1.80E+01	1.85E-01	1.80E+01	2.27E-02
1.91E+01	1.54E-01	1.91E+01	1.89E-02
2.00E+01	1.30E-01	2.00E+01	1.60E-02
2.49E+01	4.45E-02	2.49E+01	5.50E-03
3.00E+01	6.27E-04	3.00E+01	8.18E-05
3.49E+01	6.86E-05	3.49E+01	1.06E-05
4.01E+01	4.18E-05	4.01E+01	6.50E-06
4.50E+01	2.83E-05	4.50E+01	4.42E-06
5.00E+01	2.00E-05	5.00E+01	3.13E-06
5.06E+01	1.92E-05	5.06E+01	3.00E-06
5.55E+01	1.34E-05	5.55E+01	2.11E-06
6.02E+01	9.38E-06	6.02E+01	1.49E-06
6.53E+01	6.32E-06	6.53E+01	1.01E-06
7.00E+01	4.40E-06	7.00E+01	7.01E-07
7.50E+01	2.83E-06	7.50E+01	4.52E-07
8.04E+01	1.65E-06	8.04E+01	2.63E-07
8.52E+01	7.71E-07	8.52E+01	1.23E-07
9.03E+01	1.94E-07	9.03E+01	3.10E-08
9.57E+01	2.88E-08	9.57E+01	4.60E-09
1.00E+02	1.19E-08	1.00E+02	1.89E-09
1.01E+02	5.27E-09	1.01E+02	8.41E-10
1.03E+02	2.54E-09	1.03E+02	4.05E-10

Table A5
Integral LET for the October 1989 Solar Particle Event (Z=1-92)
100 mils Aluminum Shielding
Values Do Not Include Design Margins

LET (MeV*cm^2/mg)	Average Over Peak LET Fluence (#/cm^2/s)	Average Over Worst Day LET Fluence (#/cm^2/s)	Average Over Worst Week LET Fluence (#/cm^2/s)
1.00E-03	1.93E+05	5.21E+04	1.15E+04
2.01E-03	1.93E+05	5.21E+04	1.15E+04
3.01E-03	1.93E+05	5.20E+04	1.14E+04
4.02E-03	1.92E+05	5.17E+04	1.13E+04
5.01E-03	1.90E+05	5.11E+04	1.11E+04
6.03E-03	1.86E+05	5.02E+04	1.08E+04
7.02E-03	1.82E+05	4.90E+04	1.05E+04
7.97E-03	1.77E+05	4.76E+04	1.01E+04
8.95E-03	1.71E+05	4.60E+04	9.68E+03
1.01E-02	1.64E+05	4.40E+04	9.19E+03
1.99E-02	9.60E+04	2.55E+04	5.07E+03
2.99E-02	5.39E+04	1.43E+04	2.78E+03
4.00E-02	3.23E+04	8.56E+03	1.65E+03
4.98E-02	2.11E+04	5.59E+03	1.07E+03
6.00E-02	1.45E+04	3.84E+03	7.33E+02
6.97E-02	1.06E+04	2.81E+03	5.34E+02
8.01E-02	7.91E+03	2.09E+03	3.96E+02
9.00E-02	6.16E+03	1.63E+03	3.08E+02
9.99E-02	4.90E+03	1.29E+03	2.44E+02
2.00E-01	9.50E+02	2.51E+02	4.67E+01
3.01E-01	3.15E+02	8.31E+01	1.53E+01
4.02E-01	1.25E+02	3.32E+01	6.08E+00
5.01E-01	3.82E+01	1.01E+01	1.80E+00
6.03E-01	1.86E+01	4.94E+00	8.78E-01
7.01E-01	1.35E+01	3.58E+00	6.52E-01
8.05E-01	9.85E+00	2.62E+00	4.91E-01
9.04E-01	7.55E+00	2.02E+00	3.87E-01
1.00E+00	5.88E+00	1.57E+00	3.10E-01
2.01E+00	7.49E-01	2.06E-01	5.99E-02
3.02E+00	4.11E-01	1.13E-01	3.33E-02
3.99E+00	2.64E-01	7.29E-02	2.14E-02
5.03E+00	1.74E-01	4.80E-02	1.42E-02
6.06E+00	1.21E-01	3.36E-02	9.92E-03
7.04E+00	8.68E-02	2.40E-02	7.11E-03
8.00E+00	6.39E-02	1.77E-02	5.26E-03
8.99E+00	5.04E-02	1.40E-02	4.13E-03
1.01E+01	3.85E-02	1.07E-02	3.15E-03
2.00E+01	5.75E-03	1.60E-03	4.63E-04
2.52E+01	2.14E-03	5.95E-04	1.72E-04

Table A5 (Continued)
Integral LET for the October 1989 Solar Particle Event (Z=1-92)
100 mils Aluminum Shielding
Values Do Not Include Design Margins

LET **(MeV*cm^2/mg)**	**Average Over Peak LET Fluence (#/cm^2/s)**	**Average Over Worst Day LET Fluence (#/cm^2/s)**	**Average Over Worst Week LET Fluence (#/cm^2/s)**
3.00E+01	1.83E-05	5.10E-06	1.55E-06
3.53E+01	7.23E-07	2.01E-07	7.14E-08
4.01E+01	3.26E-07	9.08E-08	3.43E-08
4.50E+01	1.95E-07	5.44E-08	2.12E-08
5.00E+01	1.36E-07	3.78E-08	1.48E-08
5.55E+01	8.43E-08	2.35E-08	9.31E-09
6.02E+01	4.92E-08	1.37E-08	5.58E-09
6.53E+01	3.28E-08	9.12E-09	3.75E-09
7.00E+01	2.49E-08	6.92E-09	2.84E-09
7.50E+01	1.80E-08	5.00E-09	2.04E-09
8.04E+01	1.20E-08	3.34E-09	1.36E-09
8.52E+01	6.69E-09	1.86E-09	7.56E-10
9.03E+01	2.03E-09	5.64E-10	2.29E-10
9.46E+01	1.33E-10	3.71E-11	1.51E-11
1.00E+02	5.01E-11	1.39E-11	5.66E-12
1.01E+02	2.22E-11	6.19E-12	2.51E-12
1.03E+02	1.07E-11	2.99E-12	1.21E-12

Table A6
Differential Fluxes from Solar Proton Events
100 mils Aluminum Shielding, CREME96
Note: Spectra were cut off at E =1 MeV and E=1000 MeV
Values Do Not Include Design Margins

Energy (MeV)	**Average Over Peak Proton Flux ($\#/cm^2/s$)**	**Average Over Worst Day Proton Flux ($\#/cm^2/s$)**	**Average Over Worst Week Proton Flux ($\#/cm^2/s$)**
1.00	1.75E+03	4.62E+02	8.85E+01
2.00	2.68E+03	7.09E+02	1.36E+02
3.02	3.47E+03	9.17E+02	1.76E+02
4.04	4.11E+03	1.09E+03	2.09E+02
5.04	4.62E+03	1.22E+03	2.36E+02
6.03	5.03E+03	1.33E+03	2.58E+02
7.02	5.33E+03	1.41E+03	2.75E+02
8.06	5.56E+03	1.47E+03	2.88E+02
9.00	5.69E+03	1.51E+03	2.96E+02
10.05	5.76E+03	1.53E+03	3.01E+02
14.99	5.41E+03	1.44E+03	2.92E+02
20.03	4.50E+03	1.21E+03	2.52E+02
24.98	3.57E+03	9.65E+02	2.07E+02
30.31	2.73E+03	7.40E+02	1.64E+02
35.27	2.11E+03	5.75E+02	1.31E+02
40.49	1.61E+03	4.42E+02	1.04E+02
50.50	9.91E+02	2.73E+02	6.79E+01
60.43	6.33E+02	1.75E+02	4.58E+01
70.33	4.20E+02	1.17E+02	3.20E+01
79.63	2.94E+02	8.18E+01	2.33E+01
90.17	2.03E+02	5.65E+01	1.68E+01
100.69	1.44E+02	4.01E+01	1.24E+01
150.25	3.84E+01	1.06E+01	3.80E+00
200.77	1.39E+01	3.79E+00	1.50E+00
299.59	3.32E+00	8.62E-01	3.88E-01
400.31	1.16E+00	2.85E-01	1.39E-01
499.23	4.97E-01	1.16E-01	5.96E-02
605.64	2.07E-01	4.64E-02	2.54E-02
704.94	1.10E-01	2.48E-02	1.44E-02
798.17	6.61E-02	1.48E-02	9.03E-03
903.74	3.95E-02	8.88E-03	5.66E-03
995.41	2.65E-02	5.96E-03	3.94E-03

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14. ABSTRACT
The purpose of this document is to define the radiation environment for the evaluation of degredation due to the total ionizing and non-ionizing dose of single event effects (SEEs) for the Laser Interferometry Space Antenna (LISA) instruments and spacecraft. The analysis took into account the radiaiton exposure for the nominal five-year mission at 20 degrees behind Earth's orbit of the sun, at 1 AU (astronomical unit) and assumes a launch date in 2014. The transfer trajectory out to final orbit has not yet been defined, therefore, this evaluation does not include the impact of passing through the Van Allen belts. Generally, transfer trajectories do not contribute significantly to degradation effects; however, single events effects and deep dielectric charging effects must be taken into consideration especially if critical maneuvers are planned during the Van Allen belt passes.

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LISA, radiation environment, single event effects, Van Allen belts

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